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Race cars and the hellbox: Understanding the development of proficiency among digital art students¹

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Abstract

Educating students in the discipline of digital art to a professional standard has generally proven difficult. In an effort to understand the problem, a first-year undergraduate modelling course cohort was observed. Some students in this course progressed from being novices to acquiring proficiency during the nine-week term of the course. Computer Graphics (CG) modelling professionals evaluated student work to confirm their progress. Traditional models of proficiency development expect that proficiency is dependent on the investment of significant time on discipline-related tasks. The results of this investigation show that the transition from a novice level of understanding to that of proficiency can be rapid. Earlier models emphasize the importance of long-term memory and pattern-matching to developing proficiency. For the field of digital art, data gathered in this study do not support long-term memory or pattern matching as a principal contributing factor to the development of proficiency. Instead, it suggests that knowledge of what a professional standard is, in combination with important threshold concepts, leads to proficiency.

Keywords

learning

teaching

novice

expert

proficiency

transfer

assessment

Introduction

The first degree-granting bachelor's programme for digital arts was introduced in the United Kingdom in 1989 and the United States in 1994 (Comininos et al. 2009; Digipen 2011). Based on feedback from industry sources, most universities do not produce graduates that meet professional standards (McCracken 2006; King et al. 2008; Ip 2012; McGill 2009). To determine whether a digital artist will receive a job interview, candidate's demo reels are first screened by prospective employers. A demo reel is a collection of edited video clips delivered on DVD or a website that represents a digital artist's best work. Unlike other professions, an artist's CV becomes relevant only after this stage of the recruiting process has been successful (U.S. Bureau of Labor Statistics 2012). According to some in industry, only one of several hundred demo reels warrants an interview (Flaxman 2003). The problem of poorly qualified Computer Graphics (CG) artists is a serious one in the CG industry (Livingstone and Hope 2011). To solve it, educators in the discipline need to address the problems found by employers when reviewing candidates for positions in their work force.

We set out to explore how proficiency develops among digital artists. To do this, we asked 'How does proficiency develop among digital art students?' Our assumption was that examination of course content would not be sufficient to explain results because not all students attain proficiency. One course may allow proficiency to develop where other courses do not, but the focus here is more on student development than on course parameters.

The nature of proficiency in digital art

The term ‘proficiency’ as it is used within the CG industry describes competitive job skills. A proficient artist must know how to perform many intermediate to advanced tasks with minimal to no supervision. They are also capable of solving problems when faced with novel situations (Dreyfus and Dreyfus 2005). This is how the term ‘proficiency’ is used in this article. Proficiency and ‘expertise’ may refer to work of identical quality but for a proficient performer it is the product of problem-solving instead of a recalled solution as would be the case for an expert (Anderson and Leinhardt 2002).

The research was conducted at the International Game Architecture and Design academy (IGAD), an applied arts university in the Netherlands where one of the authors (Andrew Paquette) is the founder of the digital art programme. Data were also gathered from industry partners and employed graduates. This made it possible to observe the development of proficiency among learners as they progressed from novices to a proficient level of ability on a task that we argue is central to their development as digital artists. This article is not designed to explore work-based learning strategies, but to observe students taking part in a class where development of proficiency has been observed regularly in previous years. Looking at the problem in this way is proposed so that any successful transitions to proficiency among students can be studied independent of the intentions embedded in the class design.

We believe that there is something about the process of learning to become a digital artist that is not adequately represented or provided in most degree programmes. In this article, we will argue that becoming a proficient digital artist requires the development of cognitive abilities in the area of structural visualization in addition to acquiring the knowledge about software and concepts germane to CG that is normally taught in digital art programmes. Developing these abilities result in a new way of analysing problems and seeing potential solutions. To accomplish this, students must be engaged in problem-solving tasks that develop flexible

approaches to the way they visualize problems related to three dimensional (3D) representations of structure. This article develops this nascent area of enquiry, focusing on the nature of proficiency in digital art as a professional practice.

The problem: Workplace education and industry

Historically, some industries have preferred workplace learning to university education. This was reflected in the industry preference for employees who learned on the job or were self-taught to those educated in a university – so-called ‘hard way men’ (Wellens 1959; Musgrave 1966). This was true in the Industrial Revolution and is true today with digital art, based on complaints from CG industry sources and the U.S. Bureau of Labour (Livingstone and Hope 2011; Ip 2012; U.S. Bureau of Labor Statistics 2012).

The idea that workplace education fulfils unmet industry needs is implicit in the context of competency-based standards endorsed by government (Tight 1998; Blackwell et al. 2001), or accountability requirements in career and technical education set by professional associations (Hargraves 2000; Castellano and Stringfield 2003). This was reflected in a pair of government reports published in the United Kingdom, known as the Dearing Report and the Fryer Report, each of which supported more workplace-centric education (Tight 1998; Blackwell et al. 2001). The goal of these reports and the government initiatives that inspired them is to improve the quality of technical education by bringing students into the workplace (with internships) or by bringing the workplace to the classroom as situated learning. However, recognizing that workplace education is effective at training employees to meet industry standards is not the same as understanding how those standards are met or how those methods might be brought into the context of formal education. According to the situated cognition framework, workplace learning is effective because the learners have the benefit of a practice-oriented knowledge-rich environment.

Context and opportunity in situated learning

According to situated cognition theory, learning is always situated in a context that includes an environment and a community of practice such as at a workplace or a school (Lave and Wenger 1991). The community allows for appropriate guidance and the environment provides perspective on one's work. According to this view, the interaction between learners and legitimate members of a community of practice creates a powerful dynamic for learning within a situated context (Hall 1996). Some researchers claim that a school is appropriate only for learning skills pertinent to being a student. This is in contrast to skills germane to a specific profession that is practiced outside of the school environment (Jurdak 2006). This agrees with criticisms from the CG industry regarding the education of digital artists. Indeed, it can be argued that context and situatedness are central components of developing proficiency, particularly in the context of a profession. Without an appropriate context and legitimate members of a community of practice available for guidance, how can true proficiency develop? However, the needs of the workplace can put a higher priority on production than education, leaving learners bereft of guidance (Anderson et al. 1996). Legitimate members of relevant communities of practice are not always found in higher education institutions, but the goals held by teachers are consistent with those held by students: to learn and to eventually develop proficiency.

If workplace demands are brought into a university environment and structured for learning, students can be motivated to solve the problems presented and encouraged to work with each other in teams that simulate workplace cooperation (Rose 1999). When this happens, students have a tendency to become mentally engaged with their work to the extent that their mental models change. This is due to cognitive conflicts that occur as a by-product of social interaction (Goel et al. 2010). This view is compatible with the de Groot (1972), Chase and Simon (1973) and Goldin (1979) memory, pattern-matching, and knowledge acquisition theories of

proficiency development, but brings them together under a unifying principle that incorporates a simulated form of situated learning as a method for developing proficiency.

Workplace/formal education hybrid

Some skills may require a situated environment because they are learned through experience better than formal instruction, but instruction can improve results. In a study of physical therapy students from Mount St. Mary's College in Los Angeles, students learned how to become sensitive to their patients' range of motion thresholds in a situated learning environment (Rose 1999). This type of learning would be difficult without an environment that imitated a clinical setting. However, because instruction is involved, unlike a workplace, the student is not left on her own to discover how best to hone her technique (Rose 1999: 153–54). This is somewhat analogous to teaching at IGAD, where the standard of assessment is situated based on industry norms, but assignments and techniques are designed to compress as many learning opportunities as possible into a short span of time – thus making them less similar to what would be found in industry. To help students, teachers are available to guide the decision-making process, rather than to provide lists of instructions, as in a tutorial.

IGAD course structure

IGAD courses are designed around projects. There is a one week 'introduction project' graded as pass/fail and then a 'final project' graded on a ten point scale. Students are given two classes per week. The first is a one hour lecture held in a large lecture hall where generic information relevant to their project is provided. In these lectures, specific software is purposely not mentioned by name. The textbook used for the class also does not use the name of any software or describe tools unique to any application. By delivering application-independent information to students in lectures, the IGAD programme can be distinguished from schools that emphasize software training. In their second weekly class, a three-hour long workshop, students receive software-specific learning exercises during the first four weeks of classes. In the final three

workshops, student homework progress is critiqued for the full class period. After classes have concluded, students have two weeks to complete the projects on their own. In addition to their formal lessons, a teacher's assistant provides one voluntary attendance workshop per week during which students may receive feedback and assistance.

Methods

Participant selection

Student participants

All students enrolled in the 2012–2013 visual arts specialization at IGAD were invited to participate in this study. Of 84 students, twenty volunteered.

Graduate participants

Employed IGAD graduates were sent e-mail invitations to participate in this study. Five of these former students accepted the invitation. They resided in Canada, Belgium, the Netherlands and the United Kingdom. Two worked for the same company (in the Netherlands) but in different capacities.

Industry participants

Lecturers at IGAD invited industry contacts from their personal network to participate. An unknown number of invitations were sent out to industry experts, all of whom had a minimum of ten years of industry experience, and five accepted. These participants resided in the United States, the Netherlands and Belgium. None worked for the same company. Two had worked with IGAD graduates but did not know any of the student participants.

Researcher participant

The principal investigator in this study is one of the founders of the IGAD programme and the senior lecturer responsible for the class discussed here.

Ethical compliance

All participants were informed that they could withdraw from the study at any time without explanation or consequences. Four student participants and one industry participant withdrew from the study, leaving twenty student participants, five graduates and five industry participants. All participant names were replaced by study ID numbers to anonymize all of the data collected. After data collection was complete, the master sheet of names was destroyed. When participants are referred to in any written material relevant to this study, pseudonyms are used. The co-authors of this article (Stylianos Hatzipanagos and Gabriel Reedy) are not affiliated with IGAD in any way, and have only seen fully anonymized raw data. To prevent intentional or unintentional bias in grading, student participants' final projects were not graded by the primary investigator, but a co-lecturer who is not affiliated with the study (using the same grading rubric as used by the principal investigator to grade non-participants' work). All other relevant guidelines of the British Educational Research Association have been complied with (British Educational Research Association 2011).

Participant modules

The folding carton assignment

Of the eighteen student participants who completed the survey in phase one, eleven claimed to have had less than three months unsupervised practice in 3D modelling prior to enrolling at IGAD. Most students were beginners. The Folding Carton assignment is the first 3D project that students complete at IGAD (Figure 1).

Figure 1: An example of a folding carton assignment.

Because modelling in CG is dependent on technically flawless execution to be fit-for-use, students start off with an introduction to a professional standard. The goal of achieving the

standard is not impossible but in most years only about 25 per cent of the students accomplish it.

The folding carton project requires students to build a 3D representation of an unfolded carton using an application called Autodesk Maya (Maya). Students must then attach an image to their carton to represent its label, and fold it into its final shape without making any one of almost 100 different types of errors listed in their textbook.

The learning outcomes of the project are to:

- Introduce students to the User Interface (UI) of the software they will be using
- Demonstrate the connection between 2D and 3D space
- Introduce students to the importance of ‘clean geometry’
- Introduce the concept of accountability to end-users of their product.

Mistakes made by students on this project can usually be fixed in less than a minute, such as by renaming the file. Students only rarely claim that an error was made due to misunderstanding. The lesson is that the project is not inherently difficult, but its specifications must be respected without exception. Students are assessed against a professional standard in all classes from this point on.

Creative mental visualization and problem-solving/NURBS

There are many ways to represent 3D structure in digital art. Each of these is described as ‘geometry’. In video games, polygonal geometry is used due to the need for fast player interaction. In industrial design, NURBS are used because they are – unlike polygons – completely accurate for representing curved surfaces. The term ‘NURBS’ is an acronym but is treated as a word in industry, that convention is followed here. For the second project featured in this study, students are asked to reverse-engineer an existing automobile using NURBS

geometry (Figure 2). The project is identical in scope, complexity, subject and method to the type of project given to industry professionals. The sole differentiating factor is that students are given nine weeks to execute the project but in an industry context, about two weeks would be given, depending on complexity.

Figure 2: An example of a 3D model made for the Modelling 2 class.

Students typically want to use a familiar approach to modelling (polygons) – but the project requires them to use a more difficult form of geometry that they have yet to come into contact with (NURBS). This creates the first hurdle for students to overcome as learners – to become willing to learn new things, even when the prospect is daunting. That willingness is an important characteristic to develop in the field of digital art due to the changeable nature of the technology used.

The structure of NURBS and its demands on student practitioners

NURBS geometry requires students to be more sensitive to the topology of the design – that is, what surfaces touch other surfaces, where and how. This distinction means that the problem-solving skills they must use are completely different: as one student described it, ‘the polygon experience [that they learned in their previous modelling course] didn’t really help us... Quite on the contrary, it even... prevented us from having good results sometimes...’.

In NURBS all surfaces must be four-sided. Because most complex objects are not four-sided, they must be broken down into groups of four-sided shapes that blend together seamlessly. Complex curved objects such as vehicles might require thousands of surfaces, also called ‘patches’. Tangents of these patches must be equal to create smooth, uninterrupted surfaces. A ‘tangent’ is a direction vector measured as a position relative to a point. In NURBS modelling, a boundary between two or more surfaces will have tangents on either side of the boundary. If

the tangents have equal values, there will be no visible seam between the patches. If they are not tangent, there will be a ‘tangency break’ or ‘cusp’ that results in a visible surface deformation. To match tangents across patches, CG artists must plan ahead for the final *patch layout*, or distribution of patches across a subject’s surface (Figure 3). This is because each successive patch has the potential to alter the shape of previously built patches when it is made tangent. To get the desired result, this must be planned for in advance.

Planning ahead requires some amount of mental visualization of potential solutions, as they are tested and refined until a suitable one is found. Although most vehicles share traits, such as having four wheels, exhaust pipes, a bonnet and boot, the exact shape of these are so different from one model to the next that no single patch layout will work for any two vehicles. For reference, students work from photographs of existing vehicles. The problem inherent in this is that the reference photographs betray no evidence of where patch boundaries are located. To accomplish this stage of the task, students must conduct a shape analysis. Doing so exercises their observation and problem-solving skills at the same time as it improves their *topological awareness*.

Topological awareness is sensitivity to the way things are connected. The problem of designing a correct topology for the project is akin to solving a Rubik’s Cube, which can be looked at as a topological network problem. The reason is that the puzzle cannot be intentionally solved without retaining a mental visualization of how each of the eight corners of the cube are related to each other (Chartrand et al. 1983). In the same way, the topology of a NURBS object consists of many mutually dependent elements. Without an understanding of this structure, it is not possible to complete the NURBS project without errors.

Figure 3: Each patch in this model is represented with a different colour to illustrate the patch layout.

Mixed methods approach

Because we were interested in understanding the nature of learning in the context of developing proficiency in digital art, we selected a first-year class for observation during which students have historically first demonstrated proficiency. The class is Modelling 2, their second modelling class. To date it is always a minority of students in the class – between one and eight students out of 65–90 – who become proficient. We do not expect a majority of students to develop proficiency or that the class on its own is responsible for allowing proficiency to develop, but that this is usually the first class where proficiency of any kind is observed within the IGAD programme. Indeed, the purpose of the class is to introduce students to an alternate method of visualizing solutions – regardless whether they achieve mastery. Other classes taken later in the programme yield a higher percentage of proficient projects, but it is more difficult to evaluate those projects from the perspective of novice to proficient performance because some of those students will have developed proficiency earlier and cannot be described as novices at the start of the class.

We decided that qualitative approaches would best allow students to communicate the learning process from their point of view, but we were also aware of the potential value that quantitative measures could provide by validating that proficiency was achieved. Students are already engaged in their course work so a naturalistic way of gathering quantitative data is to take data from spatial visualization tests given to students and compare it to grades received at the end of the class. These grades can then be compared to grades given by industry professionals to see if there is a meaningful difference in the grades or the way the work is evaluated. Interviews with students were then conducted to explore how each student achieved (or did not achieve) their learning goals.

Phase one: Student tests, learning logs, grades, survey and interviews

Our study used a mixed qualitative and quantitative methodology. The qualitative methods were designed to extract insights from students and experts about their perceptions on the development of proficiency. Quantitative measures were used to validate crucial aspects of the qualitative data collected. The undergraduate students were the subjects of the study. Industry experts provided insight into their evaluative processes and were asked to evaluate a selection of student work. Employed graduates were asked to provide their perspective on the transition from proficiency to expertise. Data for quantitative tests was derived from historical archives at IGAD.

Test

IAGD students were tested on their spatial ability prior to the beginning of a first-year course in NURBS modelling (MD2). Results of the spatial visualization tests were compared with final grades for the course to determine if they were predictive of class outcomes.

Learning logs

Student participants kept learning logs, which were delivered after they turned in their final project, a 3D model of an automobile. Students were asked to make one entry per week in their logs to record significant problems and successes related to the NURBS project. They were also encouraged to make comments related to their perception of progress.

Survey

After all project grades had been published, students were asked to take a survey regarding their experience of the course. The survey was broken into three sections: demographics, Likert scale questions about the learning experience, and open-ended opportunities to raise any concerns related to the course. The questions were designed to identify problems experienced by students in the course that could be explored in greater detail during interviews.

Interviews

The learning logs and surveys were used as the basis for a one-hour, semi-structured topical interview that would give students an opportunity to explain their survey answers and anything they may have written in their logs.

At IGAD, all students must pass an English-language proficiency test before being allowed entry to the school and all classes are taught in English. Therefore, although none of the participants in this study speak English as a first language, problems with English were unlikely to affect the accuracy of statements made by students. Because all data collected refers to objective products, lack of English fluency was not a factor in the evaluations. The only language-related effect observed was reduced detail in answers from some students during interviews.

Phase two: Professional feedback

In phase two, we showed industry participants ($n=5$ managers) a subset of student projects during separate one hour interviews. They were asked to evaluate student projects against the standard used in their place of business. Industry participants were then asked to convert their assessment to a numerical grade on a ten point scale, where a six was the lowest quality level that was acceptable for industry use and a ten was exceptional. After grading the assignments, Industry experts were asked to describe the assessment process and to answer questions regarding their expectations of graduates. The goal of this was to determine whether the academic standard for proficiency matched that used by industry experts.

To determine whether the five industry professionals applied similar grading standards, all were shown the same four vehicles. Only the four highest scoring student projects were shown to experts. The three reasons more projects were not shown are: (1) the experts had time for four projects, based on the assumption it would take fifteen minutes to evaluate each file, (2) to explore how proficiency was developed, examples of proficiency had to be identified and

validated first. The probability of finding examples within the time limit of the interviews was enhanced by providing only the strongest files identified by project grades. (3) If industry evaluations agreed with academic evaluations, an inference could be drawn that academic evaluations of models not shown to industry experts would be consistent with industry.

Phase three: Employed graduate interviews

In phase three, we interviewed graduates of the programme ($n=5$) to understand more about how former students transitioned from their performance in university to working in industry.

Results

Phase one: Student tests, learning logs, grades, survey and interviews

Of the twenty students who signed up for the study, five did not take the tests. However, their interviews, survey answers and project evaluations can be used. This means that there are fifteen full sets of results and five partial sets. In addition to this data, historical IGAD student performance data was used for tests to determine statistical significance.

Test: The Purdue Visualization of Rotations Test

The Purdue Visualization of Rotations test (PVRT) was given to IGAD students from 2010-2011 and to study participants in 2012 as a way to measure their spatial ability prior to being exposed to any of the NURBS modelling classes. A Spearman's rank-order correlation was run to assess the relationship between grades earned in the MD2 class (MD2) and PVRT scores. Preliminary analysis showed the relationship to be monotonic, as assessed by visual inspection of a scatterplot. There was no correlation between MD2 scores and PVRT scores, $r_s(109) = .185$, $p < .052$. This is quite different from the result from the MD1 (polygon modelling) comparison with the PVRT results, which strongly correlated. ($r_s(109) = .330$, $p < .0005$). A Kruskal-Wallis test was conducted to determine if there were differences in MD2 scores between four previous education group types, where MBO students had previous CG

experience and other groups did not: "MBO" (n=164), "HAVO" (n=267), "VWO/GYM/LYC" (n=101) and "Foreign" (n=76). Distributions of MD2 scores were not similar for all groups, as assessed by visual inspection of a boxplot. MD2 scores were statistically significantly different between the different types of previous education, $X^2(3) = 17.291$, $p = .001$. Subsequently, pairwise comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons. Adjusted p-values are presented. This post hoc analysis revealed statistically significant differences in MD2 scores between the HAVO (mean rank = 272.67) and MBO (mean rank = 325.42, $p = .008$) and HAVO (mean rank = 272.67) and Foreign groups (mean rank = 347.93, $p = .008$), but not between any other group combination. The MD2 grade mean between HAVO and MBO students favoured MBO students by 0.99 grade points. The MD2 grade mean between HAVO and Foreign students favoured Foreign students by 1.33 grade points.

To determine what effect missing files had on results, A Kruskal-Wallis test was conducted to determine if there were differences in MD2 scores between six previous education group types if scores of zero and one were excluded. The groups compared were: "MBO" (n=123), "HAVO" (n=167), "VWO/GYM/LYC" (n=74), "Foreign" (n=58), 'over 21' (n=11), and HBO (n=1). Distributions of MD2 scores were not similar for all groups, as assessed by visual inspection of a boxplot. MD2 scores were not statistically significantly different between the different types of previous education, $X^2(5) = 7.925$, $p = .160$. This result is different from when the same test was run on MD1 scores with grades of zero and one excluded. In that test, MBO students (mean=6.48, n=162) had a 0.95 grade point advantage over HAVO students (mean=5.53, n=264) and foreign students (mean=6.13, n=76) had a 0.60 grade point advantage over HAVO students.

Learning logs

Results from the learning logs were disappointing because only seven of eighteen participating students turned in a learning log. Two groups of friends provided all of the logs that were turned in. One group was all female ($n=3$) and attended higher level secondary schools (VWO and Gymnasium) before enrolling at IGAD. The second group was all male ($n=4$) and attended lower level MBO schools before coming to IGAD. Of the nine students who received a grade of eight or higher on the NURBS project, only two turned in a learning log. Three of the students who filled out a log failed the class, the other four did not. The full range of performance, from a failing grade of 4 to a high of 10, is represented by the group of students who turned in logs. This indicates lack of bias, but bias would only be a confounding factor if these logs were used in a statistical analysis. The value of the logs is not to establish statistical significance, but to capture notes relevant to the development of proficiency, particularly if that can be used to support observations of progress in class, statements by students in their interviews or surveys, or the expert analysis of their final project. Some key observations extracted from logs belonging to different students are presented in Table 1.

Table 1: Excerpts from multiple student learning logs.

Week	Student comment	Note
2	‘Now that I look at that complicated shape again, I realize that I chose the least convenient way of building it, which means I will have to redo it. At least I have an idea how, which I shall count as a success for now’	Shows early awareness of construction order (this student’s project received the highest grade)
4	‘Slowly – painfully slowly – the giant heap of loose paper sheets starts to look like a car’	Awareness that precursor shape (paper sheets) has

		different appearance (shape) than final product
6	‘I have a few issues with the order of witch [<i>sic</i>] I create surfaces. The main problem is that after I have builded [<i>sic</i>] a part of the car, I find that other parts would have been easier to make first’	Understands construction order problem
7	‘What first took me an entire week can be done in a couple of hours now’	dramatic speed enhancement implies that speed of execution is a matter of knowledge or technique rather than quantity of work or difficulty of problem
8	‘Remaking shapes/blends has (I think) increased my way of seeing problems and it actually improved my drawing skills’	Connects quality of ‘seeing’ (visualization) with problem-solving skills and transfer to a different discipline (drawing)

Weekly progress images

As an alternative to the learning logs, weekly progress files were converted to images as a way to follow student progress. These images reflect the state of each student’s vehicle model at the end of each week, except for weeks where no progress was made (Figure 4). These are available for all students, thus providing an accurate weekly record of their progress during the class.

Figure 4: Weekly progress NURBS assignment.*Survey*

The surveys were completed online by seventeen of the twenty student participants. The remaining three student surveys were completed during their respective interviews. The surveys were used as the basis for interview questions rather than to establish any kind of statistical argument. For that reason, most of the survey results are embedded in the interview results and will be described there. An exception to this are open questions that were considered answered in full on the survey. Some comments of interest are presented in Table 2.

Table 2: Excerpts from survey answers.

Question: What did you like least about MD2?	Researcher comment
‘... it also was very difficult to get some surfaces to align properly with the rest of the surfaces’	Alignment, or tangency, is a patch layout problem
‘... I had a hard time figuring it out’	Consistent with problem solving.
‘... A difficult car takes longer to understand’	Recognition that solutions are not interchangeable among different vehicles
‘Getting used to the new tools. I can see how the objects are made but it is hard to find the right tools to make it’	Implication that patch layout step, and thus the primary problem, has been skipped
‘The period of stress. Though it pushed me towards greater results, it was difficult going	Consistent with threshold concepts

through this phase from being a complete novice. I didn't like it at the time but afterwards it feels good to have survived it'	
'It was hard for me visualize the shape when I started out'	Visualization connected to central problem of project
'The amount of time you have to spend on continuity – I always kept spotting tiny errors and spending too much time trying to fix those, rather than working on the entire car'	Tendency to ignore connections between features of the vehicle implies lack of coherent strategy for patch layout
Question: What did you like the most about MD2?	Researcher comment
'The fact that I learned A LOT. Every single day, hour and minute I spent on my NURBS project, I learned something new. It astonishes me when I look back at the beginning, and see how much I've learned in just 3 blocks'	Indicates stronger than usual learning experience
'... it's hard to make tangent, all the surfaces offer a challenge [<i>sic</i>] that make me want to bash my head against the wall in desperation. Conquering each one, one at a time, is causing me to rapidly increase my skills with nurbs [<i>sic</i> ']	Potential indicator that threshold concept is related to method for making surfaces tangent

‘... this excersize [<i>sic</i>] is a very good way for newcommers [<i>sic</i>] to get an understanding of topology’	Indicates importance of topology to project
‘The fact that everyone has the same base knowledge when the project starts. This way the chances of success are equal and one can easily see how students learn and become more self-confident while they progress without being affected by prior experience’	Awareness that prior experience (in polygon modelling) does not affect performance on the NURBS project

On the survey, students were asked how much previous experience they had with CG. Broadly speaking, the results can be broken down as belonging to two groups: former MBO students who had two or more years of experience, and all other participants, who had no more than three months experience (Table 3).

Table 3: CG experience prior to enrolling at IGAD.

		Frequency	Percent	Valid Percent
Valid	MBO	162	25.8	25.9
	HAVO	264	42.1	42.2
	VWO	101	16.1	16.2
	Foreign	76	12.1	12.2
	Over 21	17	2.7	2.7
	HBO	5	.8	.8
	Total	625	99.7	100.0
Missing	System	2	.3	
Total		627	100.0	

Interviews

In the context of determining whether knowledge of polygonal modelling techniques affected their status as beginners with NURBS modelling, one former MBO student reported his impression that ‘... NURBS is a completely different thing and I now have four year[s of] experience in polygons but it’s not the same as NURBS’. Another student had this to say ‘... it’s different than Polygons – it’s totally different’. These sentiments were echoed by other students who had experience with polygon modelling, some of whom stated their opinion that knowledge of polygonal modelling techniques interfered with their ability to learn NURBS modelling due to significant differences in the constraints of each geometry type.

Demographic questions were designed to determine whether students felt that any factors outside of the classroom influenced their progress. The following items were checked: travel time to school, living arrangements, part time jobs, age or previous school type. Only one student claimed that any of these factors (travel time) played a role in his learning experience, but his performance on the NURBS project and overall academic results were good (NURBS grade=8, ECTS=58) despite this.

Some interviews contained insights regarding the learning process. One item worth mentioning was a response to the survey question ‘Are there any MD2-related subjects you would like to address during the interview?’ One student wrote ‘The short moment of clarity when I suddenly realized how NURBS modelling works’. During the interview, the student explained how, in the sixth week of classes

... I had the feeling that I was going to fail this course, and that made me think, that made me care less about the result because I was afraid to fail, and that also made me try different things, because well, I wasn’t afraid to fail anymore.

This allowed him to suddenly change the way he visualized the shapes needed to build his NURBS vehicle. This was an ‘aha’ moment for him, that caused a dramatic improvement in the quality of his work product.

Other students were asked to describe any significant transitions in their learning or ability on the project. They identified more than one factor that they felt was causative of any noticed improvement. These factors fall into three categories: tool knowledge, confidence/willingness to experiment and visualization. Students were also asked to identify when any transitions occurred. The answers varied from student to student, but tended to cluster based on which of the three transition categories was pertinent to the answer.

Tool knowledge transitions, that is, the transition between not understanding the tools and understanding them, happened throughout the entire duration of the project or not at all ‘... really near the end... a big thing was I didn’t understand it at first, that you were allowed to move parts of the hull...’, ‘No, I just, prior to that class, I just was figuring out how NURBS exactly work’. Students who did not experience this transition also did not experience the other two: ‘Getting NURBS vision – as in how would something like that consist of shapes and how would I cut this out of that, and I had a really hard time getting used to that’.

Confidence/willingness to experiment transitions were reported between weeks one and seven of the course. Only one student reported it in the first week, however, with all other students saying they became more confident and willing to experiment in the third week or later. This quote is typical of students who mentioned this:

There was this part at the back of the car that there was a really nasty tangency error and I have worked on it for about two/three days straight without any progress. And I tried everything to my knowledge to solve it but it didn’t work out and eventually I tried something else and it so

happened to solve the problem. But it was in a way that I least expected it to work.

Students who did not report the confidence/willingness to experiment transition also did not report encountering the visualization transition.

The visualization transition tended to happen late in the project, between weeks five and eight, but three students reported it earlier. The one student who reported this occurring in the first week of classes is also the only student to report having had prior experience with a style of drawing that is closely identified with the industrial design and automotive design industries. A small number of other students had some prior drawing experience, but only this one student had experience so closely associated with the subject matter of this project. More typical is this week four transition described by a different student:

And you had to look at the shape of the car and cut it out, and normally with headlights you don't expect them to be part of the car, you expect them to be like this separate object that should be built separately. But it's actually just a cut out of the big shape in the hood of the car, and yes, that took me also till week four to actually figure that one out.

Several students claimed to have acquired the habit of reflexively analysing the structure of objects in their immediate environment during or after the NURBS class:

And actually, I see everything around me is kind of made of NURBS; all the shampoo bottles, everything. I just can't get it out of my mind. All the cars I see in the street, I just automatically analyse it; how can I cut it, how can I blend it...

At IGAD, automatic shape analysis is jokingly called 'NURBSvision', but it describes a real outcome of the class for many students.

Due to problems speaking English, several students preferred to answer simple questions that did not require much exposition on their part. This means that for these students, there are no quotes where they clearly describe the learning process in their own words. What their interviews capture instead are exchanges that provide some insight into their learning process, such as the following:

AP So would you say that the frustration you felt was related to the shape analysis factor?

P26 Yes.

AP Okay, so can you explain to me if there is any difference in the way you analyse shapes prior to you suddenly understanding how NURBS work and after, and if you can describe that? [silence] Can I give you an example?

P26 Yes, please.

AP Okay. One of the other guys I was talking to said that after he felt like he suddenly understood NURBS, when he was walking around at the train station for instance, he is automatically analysing every shape he sees,

and he has a pretty good idea of how things break down, but before that he wasn't doing that.

P26 I have the exact same thing.

Overall, student interviews described more or less complete learning trajectories. Students who earned the highest grades also described a wider variety of elements in their learning process. Students who received the lowest grades tended to focus on tool knowledge in their interviews. The picture that emerges from this is of a group of students learning at different paces.

General feedback

Phase two: Professional feedback survey and interviews

In total, there were four vehicles submitted to each of five industry participants. All of the industry participants agreed that the vehicles met a professional standard, however, they disagreed slightly on the degree of proficiency (Table 4).

Table 4: Industry grades scaled to match academic grading scale, and means compared.

Scaled industry grades	Student			
	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
Reviewer 1	8	8.5	9	9
Reviewer 2	9	8.75	9	9.25
Reviewer 3	8	9	8.5	10
Reviewer 4	8.5	9	8.75	9

Reviewer 5	9	8.75	8.25	9.5
Mean	8.5	8.8	8.7	9.35
Academic grade	10	9	8	9
Difference	1.5	0.2	-0.7	-0.35

In each case, Industry participants stated that they had worked with employees who had presented work at the same level of quality or worse. This was a surprise to them, particularly when they learned that the models were made by first-year students in their second modelling class, not graduated students, as they had expected.

The industry participants liked the fact that students were rated against a professional standard, because it helped prepare them for real-world working conditions. As one participant put it: ‘I will expect [of students] that they arrive at [graduation] doing stuff that some of our professionals can do and this is why: because the thing to remember is that... our industry is constantly evolving’.

Industry participants also appreciated that the goal of the project emphasized problem-solving and visualization rather than application-specific tool usage. As one of these participants stated, ‘We encounter unknown problems and we’re dealing with challenges that we haven’t dealt with before, even though we’re making it probably for the fourth time...’

Industry participants were asked about their evaluation criteria to determine if there were any meaningful differences from academic assessment criteria. They emphasized the importance of fidelity to the subject – or ‘likeness’ – as in this quote

... this is game-worthy, this model. In the PlayStation 2 era, this would be like thrown in any racing game in a heartbeat, so... especially with the detail on the back. He has a

good feel of shape, the artist. The model again doesn't feel off. It feels pretty consistent, really.

All participants checked models for technical errors, but this was always done after the likeness was checked. Technical errors were not considered to be as important because '... I think those are fixable, I don't think that's going to be a difficult... I mean all the geometry was there in the right place'. They all insisted that technical errors would have to be fixed, but that determining proficiency is more reliant on an artist's ability to make a good likeness than whether they have made technical errors.

Phase three: Employed graduate interviews

Employed graduates were asked about their job responsibilities to determine whether they were tacitly acknowledged to be experts by their employers. Based on their answers, four of the five could be described as 'experts' because their jobs require them to find (and solve) problems, evaluate the work of other professionals, and their own work product is used to guide less experienced artists. These former students were asked to reflect on their learning process at IGAD to determine when they made the transition to being proficient, and then when they felt they became experts.

The graduates said they did not feel as if they had become experts until their graduation projects at the earliest or after they had started working professionally, if at all. The graduate participants agreed that they had made proficient work in various classes prior to their graduation. They each selected different projects as the first proficient project they made, but each example was a project where they felt inspired to explore its boundaries by pushing it as far as it could go. This was similar to how they described their first examples of expertise, but those were an extension of something they had done earlier to a proficient standard.

As an example, one former student described his anatomy project, a project where he had to build a 3D model of the human skeletal and muscular system, as an example of his first proficient project. In his last year at IGAD, he built a complex character model that benefitted from the earlier anatomy project. Unlike the anatomy project, he set his own goals and standard for the graduation project, leaving him free to explore the problem bounds himself. At this point he was problem-finding and designing his own *pipeline*, industry jargon for a working solution to a common problem. He did not describe himself as an expert after this project was complete, but acknowledged that the standard the model met was in some ways higher than what is expected at his office and that his ability to conduct pipeline work as part of his job was similar to the work he did on his graduation project.

A student described his transition to expert behaviour in the context of a team meeting at the office he currently works at ‘I can just read the task or just hear from the producer and I’m already starting to think about all the ways I can achieve this and I can already sort it out actually which one of those ways are the best’. He went on to say that before he noticed that he was doing this, he would listen to tasks as they were given out, either in school or at work, but reacted passively to them rather than automatically visualizing potential solutions. He notes that he can see junior artists on the team are passive in the way he was prior to his transition to expert behaviour. They are capable of executing the work once it is given to them, but do not have the experience to visualize the instructions as they are read. This makes it impossible to evaluate the assignment until after they have started working on it.

Some industry participants commented on the importance of ‘professionalism’ as a skill. According to one, the professionalism of IGAD graduates is so well-known to employers that it is axiomatic. Several of the employed graduates stated that the CG knowledge and skills they picked up were important to them, but even more important was professionalism, because this

made it possible to evaluate their own work and behaviour in the context of a workplace environment and the demands of industry.

Discussion

Prior experience

It would be reasonable to expect that higher levels in the Dutch education hierarchy would produce students that earn higher grades on the vehicle project. The same expectation is logical for students who have more previous experience with CG than other students, yet this expectation was only realized for polygon modelling, not NURBS modelling. For the Carton project—a project that most students fail (67%, $n=625$), MBO students passed more often than HAVO students by a 6.2% margin. On the MD1 polygon modelling project, a comparison revealed statistically significant differences in grades earned by the MBO and HAVO student groups. The difference favoured MBO students by .91 of a grade point. A similar test was run for the MD2 project, and again, MBO students outperformed other groups by a statistically significant degree. In comparison to HAVO students, the mean improvement on MD2 grades was .99 of a grade point.

On its face, these findings clearly suggest that former MBO students had a meaningful general advantage over HAVO and other students in modelling classes. However, an inspection of the data showed that MD2 statistical test results were influenced by the number of students who didn't turn in a project. These students, depending on what year they were in, received grades of zero or one for not turning in a file. Grades of zero and one do not reflect 'performance' in the sense that there is no performance to assess, even if a grade was registered. To correct for this, new statistical tests were run on the MD1 and MD2 grades, but this time filtered to remove grades of zero and one. The results of the new tests were almost identical for the MD1 project, a .95 grade point advantage to MBO students over HAVO students, but for the MD2 project,

there was no statistically significant difference between any student groups. This finding suggests that prior experience in polygon modelling—the type of modelling taught at MBO institutions—does benefit students on polygon modelling assignments but not on NURBS assignments. This is supported by students, most of whom stated that polygon modelling experience was not helpful and in some cases was even detrimental to their efforts to learn NURBS modelling.

The prior experience MBO students had is with polygon modelling only. This could be looked at as a reflection of the MBO system rather than an implication that polygon modelling experience has a negative impact on learning as some students claimed. However, even when restricted to a discussion of polygon modelling, MBO students did not feel they had a significant advantage due to their prior education (Table 5). When asked about this a former MBO student had this to say,

Well, I thought it would be like... I know how to model, I know the terms... And I know that from my previous education, so it gave me the advantage during the test, because I know those things. But all the other things like Maya and ZBrush and those sorts of things are new for me, so it wasn't an actual advantage [on the NURBS project].

Table 5: Vehicle grade categories, sorted by previous education type

MD2PassType					
PrevStudyNumeric			Frequency	Percent	Cumulative Percent
.	Missing	System	2	100.0	
MBO	Valid	Fail both attempts	66	40.7	40.7
		Fail original pass retake	36	22.2	63.0
		Pass original	60	37.0	100.0
		Total	162	100.0	

HAVO	Valid	Fail both attempts	136	51.5	51.5	51.5
		Fail original pass retake	47	17.8	17.8	69.3
		Pass original	81	30.7	30.7	100.0
		Total	264	100.0	100.0	
VWO	Valid	Fail both attempts	40	39.6	39.6	39.6
		Fail original pass retake	17	16.8	16.8	56.4
		Pass original	44	43.6	43.6	100.0
		Total	101	100.0	100.0	
Foreign	Valid	Fail both attempts	28	36.8	36.8	36.8
		Fail original pass retake	19	25.0	25.0	61.8
		Pass original	29	38.2	38.2	100.0
		Total	76	100.0	100.0	
Over 21	Valid	Fail both attempts	8	47.1	47.1	47.1
		Fail original pass retake	2	11.8	11.8	58.8
		Pass original	7	41.2	41.2	100.0
		Total	17	100.0	100.0	
HBO	Valid	Fail both attempts	3	60.0	60.0	60.0
		Fail original pass retake	2	40.0	40.0	100.0
		Total	5	100.0	100.0	

This suggests that prior experience with 3D digital art tools, provided that experience does not include NURBS modelling, has no impact on performance in NURBS modelling tasks.

The results showed that the PVRT test is not predictive of performance in the MD2 class. This is consistent with work done at Coventry University, where automotive design students were given the Purdue test but results did not correlate with student performance (Osmond et al. 2009). These two results conflict with other examples of the Purdue test being used, where they are predictive of academic outcomes to a significant degree (Bodner and Guay 1997). What the Coventry study and this one have in common – unlike other examples described in the literature – is that both involve students who utilize Computer-Aided Design (CAD) tools to accomplish design objectives. Students in the Bodner study, for instance, were studying chemical engineering, science, agriculture and biology.

Visualization thinking

NURBS are known by industry experts to be difficult to work with due to their built-in topological limitations (Gao et al. 2006; Müller et al. 2006). For automotive designers, creating smooth transitions between NURBS surfaces (fluid surfacing, double curvatures etc.) is considered a threshold concept (Meyer and Land, 2012: 12). However, subsequent work (see Osmond et al., 2009) found another threshold concept in this area related to the thinking processes that were needed before gaining skills and abilities. The threshold concept identified by Osmond et al. was the toleration of design uncertainty – defined as the moment when ‘a student recognizes that the uncertainty present when approaching a design brief is an essential, but at the same time routine, part of the design process’. First this is overcome, and then students are enabled to acquire a new way of visualization of 3D curved surfaces that allows them to visualize how smooth surface transitions may be made in NURBS modelling. This threshold concept could be defined as ‘visualization thinking’, or as one student said ‘the short moment of clarity when I suddenly realized how NURBS modelling works’.

Applying the threshold concept characteristics to visualization thinking shows a good match for a threshold concept (Table 6). This means that at least some of the problems faced on the project are problematic to the learner, knowledge or methods connected to solving the problems are often irreversibly changed, and the solutions must be learned to progress in one’s knowledge of a given subject (Meyer and Land 2003).

Table 6 Visualization thinking compared to characteristics of threshold concepts, table based on Baillie et al. (2013).

Transformative	Understanding a threshold concept can result in a personal as well as conceptual change – people are required to move outside of their comfort zone and enter, sometimes disconcerting, new territories. This happened
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	to students who found that they had to radically change the way they visualize solutions to the NURBS problem.
Irreversibility	Once understood never forgotten. Students who successfully navigated the NURBS project reported changes to the way they evaluated shape-related problems.
Integration	Opening up of connections between different experiences: ‘the landscape is different’. The new way of visualization became embedded in the way they approached problems.
Troublesome	New knowledge fights with old knowledge. Students resisted using NURBS modelling techniques demonstrated in class because it conflicted with familiar working methods and seemed illogical because it could not be solved on the basis of explicit knowledge.
<p style="text-align: center;">Liminal space</p> <p>While the above happens, people can get stuck when they struggle to let go of the old and integrate the new. All students report this happening, but only a few successfully navigated the project on the first try. Several who initially failed succeeded later with a retake. Once accomplished, their approach to problems was meaningfully altered.</p> <p style="text-align: center;">Outcome=new identity</p>	

Jan Myer – one of the originators of threshold concepts as a theory – stated that there were two ‘non-negotiable features’ of threshold concepts – that threshold concepts are always epistemologically and ontologically transformative (Quinlan et al. 2013). This means that once acquired, the way a student experiences subject matter relevant to the concept is meaningfully

altered. This matches the results from successful students on the NURBS project, all of whom found that confronting surface transitions (the threshold concept) had the effect of enabling a new kind of visualization thinking that allowed them to make a functional topological analysis of their subject.

Student feedback consistently pointed to a profile of the learning experience that could be stated as follows: the carton project introduced students to professional standards regarding craftsmanship, and then the NURBS project enhanced their observation skills by exaggerating errors to such a degree that students felt compelled to fix them. By the time students neared the end of the project, a handful of students had discovered how to visualize simple and efficient solutions to the NURBS problem. At the same time they discovered that these solutions allowed rapid execution of the project. At this stage, most students threw away whatever they had made and started over.

Not all students learned how to visualize solutions for reverse-engineering their vehicle. Interviews with these students centred on problems with tool use and difficulty understanding how to breakdown the surface of an auto body into separate tangent NURBS objects by using different tool combinations. This method assumed that tool knowledge alone would solve the problem, but this was not the case. These students did not comment on the likeness of their vehicle as often as students who succeeded at visualizing appropriate solutions to the NURBS problem. They missed the connection between likeness, visualization and a successful topology.

Expertise and proficiency

Expertise research suggests that many years of practice are required to achieve an expert level of fluency in any given domain (Chase and Simon 1973; Ericsson and Charness 1994). This study shows that digital art students can achieve results on a complex task that are as good as or better than what is expected of a working professional after completing a nine week class. In

this study, some student participants meet the Dreyfus and Dreyfus standard for ‘proficiency’ because they are capable of solving problems but have not solved enough problems yet to be able to reliably recall previously worked out solutions (2005). This proficiency standard is well-described and easily identified in the data collected for this study. The Dreyfus definition is part of their ‘stage model of expertise development’ (2005) and represents the penultimate step prior to becoming an expert.

There is considerable variation within the literature of expertise regarding what kind of skill or knowledge is sufficiently complex to warrant being described as ‘expertise’. In Simonton’s expertise studies, he tends to focus on examples of historical genius, such as the astronomer Galileo Galilei, Thomas Edison or famous composers of opera (2012, 2014, 2000). On the other end of the spectrum, comparatively simple skills, such as recognizing faces and restaurant order-taking are also considered to be examples of expertise by other researchers (Wong et al. 2009; Ericsson and Polson 1988). Between these extremes lie a number of professional skills that generally require some training to master and that, once mastered, have commercial value. For instance, competitive chess (Hambrick et al. 2014) or athletics (Barker et al. 2014) and medical diagnosis (Ericsson et al. 2009). These are the type of skills that best suit the Dreyfus definition of expertise as well as a category of skill that NURBS modelling belongs to: professional, commercial and requires lengthy training to practice professionally. However, the amount of training required appears to be less than the 10,000 hours or ten years suggested by Ericsson and others as an approximate requirement (2014). In this study, novice students developed proficiency in a complex task within nine weeks. Employed graduates claimed that their next milestone in performance, when their job responsibilities indicated that they had become experts, was between six months and two years after their first example of proficient work in the same specialty.

Upon examination, work by the students in this study indicate that they do not need a broad knowledge base, strong long-term memory, or pattern matching skills to execute the work demanded of them. Instead, they need visualization thinking in addition to certain types of knowledge relevant to the specific domain and problem they have been asked to solve. The visualization of problems and their solutions has the effect of structuring pertinent knowledge into a knowledge network or topology.

The outcome of developing proficiency in this way is that students find themselves more confident overall because they know they understand the problem. This allows them to analyse other problems similarly by first defining the scope of a problem space and then looking for relevant knowledge and structural connections to the problem. Unlike teaching methods that emphasize broad acquisition of knowledge without drawing attention to relevant connections between that knowledge and problems students might be expected to solve, by emphasizing visualization thinking, digital art students can be assisted to achieve proficiency in a short amount of time.

The fact that schools specializing in training digital artists have such a poor reputation among industry experts implies a problem in the way students in this discipline are taught. This research demonstrates that students can be taught to be proficient, that it does not have to take a great deal of time, and that the results are consistent. If, as research suggests, this is not the case at most schools then perhaps it is because they are not training students to be professionals but are instead only being introduced to the field, without making the connections between knowledge, practice and standard.

This article is intended as a recommendation that professional standards be applied as early as possible in CG for visual artists, and that visualization thinking is incorporated into practice-based curriculum.

Note: On sources for industry-related data

The CG industry has been the subject of many industry research projects, conducted internally or by external research organizations. Reports conducted for the purpose of providing information useful for business strategies, are not only expensive (reports sampled during the literature review here cost between \$2200 and \$4450), but cannot be purchased by academic institutions.² Internal reports are generally unavailable outside the company, and are restricted to ‘need to know’ employees on the basis that they constitute trade secrets. Research has also been conducted for trade publications in the industry, such as job-related surveys for gamasutra.com, a website that targets the global video game industry. This information is published in non-peer-reviewed articles on their website. Another source of data is industry conferences, but not all presentations are peer-reviewed as rigorously as would be the case for a journal. One of the few publicly available rigorously collected data sources on the subject is the U.S. Bureau of Labor, which provides information relevant to the US job market for various industries. Another source was a report commissioned by a British charity for the purpose of improving the employability of graduates from British CG programmes.

There are numerous problems associated with finding accurate peer-reviewed data relevant to CG industry hiring practices. However, the information does appear in non-peer-reviewed sources. Because it is not central to this article, the sources used for industry-related hiring practices are industry insiders as found in conference proceedings. These are not ideal sources, but they are consistent with each other and the principal author’s own experience as a former industry insider. The sources are most easily found in publications from the United States, United Kingdom, Japan and China, due to the concentration of CG-oriented businesses in those locations. Although the student participants of this study are from the Netherlands, their training is for the global CG industry.

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Notes

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² When the IGAD programme attempted to purchase some of these reports from the NPD group, they were refused as a client after NPD enquired about IGAD's business type and learning that it was an educational programme.